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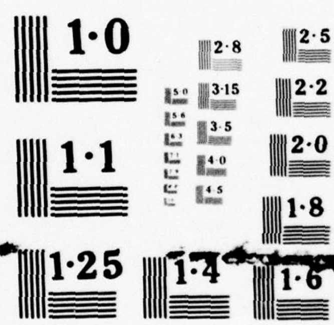

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

CIRCULATION CONTROL AIRFOIL STUDY

PROGRESS REPORT NO. 4

LOUIS V. SCHMIDT

NOVEMBER 1977

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The prime goal of the investigations described in the Progress Report has been the evaluation of the unsteady aerodynamics, and in particular the transfer functions, applicable to the Circulation Control Airfoil (CCA) for the situation of harmonic blowing perturbations superimposed upon a mean cavity pressure. Circulation control was achieved upon the relatively thick (t/c = 0.214) elliptically shaped two-dimensional air- → over

foil by tangential jet injection at an upper surface slot just ahead of the rounded trailing edge.

The experiments were conducted in the Naval Postgraduate School unsteady flow 2 x 2 foot wind tunnel. Preliminary results were obtained disclosing the nature of unsteady surface pressures over the airfoil, both amplitude and phase, relative to the oscillating cavity pressures for a range of reduced frequencies, k = 0 to 0.46, at a model attitude approximating the zero lift condition (blowing-off) at a moderate value of momentum blowing coefficient. Positive results were obtained towards identifying the behavior of the Coanda sheet dynamics, airfoil lift transfer function and airfoil damping moment.

ABSTRACT:

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1. INTRODUCTION:

It is the purpose of this overview-type progress report to describe the principal accomplishments of the unsteady aerodynamic research program on the Circulation Controlled Airfoil (CCA) conducted at the Naval Postgraduate School (NPS) through the end of the Fiscal 77 funding period (ending 30 September 1977).

The work described herein was previously outlined under the category of future efforts in the third progress letter dated 12 December 1976, Ref. 1. Since that time, five thesis students have contributed to the program by individual efforts as summarized below. Abstracts of the reports may be found in Appendix A.

a. LT J.L. Bauman, Ref. 2, developed and confirmed the operation of a control valve in the pressure supply line just upstream of the airfoil cavity so as to permit the superposition of a harmonic pressure perturbation upon a mean value of cavity pressure. Subsequent analyses disclosed that second harmonic distortion in the pressure cavity typically was on the order of five percent or less of the fundamental harmonic perturbation. It is this latter aspect of the airfoil cavity pressure signal which made possible its use as an analog clock to synchronize the timing of the unsteady airfoil surface static pressure measurements.

b. LT B.M. Pickelsimer, Ref. 3, developed a numerical algorithm that employed cross-correlation techniques for identifying Fourier components in multi-channel, discretized, truncated signal information without reliance upon zero crossings of the reference analog clock channel. This technique subsequently allowed the determination of amplitude and phase angle of the various data channels relative to the reference clock channel (unsteady cavity pressure). Additionally, the procedure for determining the in-phase and out-of-phase lift coefficient components from unsteady pressure data were described and demonstrated for a sample situation. For the sample case, the airfoil's self-induced oscillating pressure traits, which had been acquired by direct analog recording, were employed. The limit cycle pressure behavior was observed as a single frequency (variable amplitude and phase) over the complete CCA when tangential blowing was discontinued in a low range of operating Reynolds numbers.

c. LT E.J. Lancaster, Ref. 4, reported upon the steady flow behavior of the CCA following a complete refurbishing of the trailing edge slot and static pressure orifices. Lift augmentation ratios of the order of 30 were reported in contrast to the values of 15 previously reported, Ref. 1. The increase in augmentation ratio was attributed to the improved condition of the refurbished trailing edge slot. In addition, a dynamic flow calibration of the NPS oscillating flow 2 x 2 foot wind tunnel was performed and results comparing pressure and velocity perturbations for a range of rotating shutter frequencies were reported.

d. LT K.A. Kail, Ref. 5, investigated the behavior of the Coanda sheet formed by the tangential jet flow over the airfoil's rounded trailing edge. His observations were primarily based upon a hot-wire traversing system that was developed specifically for the CCA installation. In addition, he amplified upon the airfoil static pressure measurements of Ref. 4, and in particular, noted that the superposition of an oscillatory blowing component upon the steady tangential jet flow did not produce any discernible change in the mean or average value of lift augmentation.

e. LT C.D. Englehardt, Ref. 6, completed the "keystone" item necessary to integrate the efforts of Refs. 2 through 5, and it is this development which finally made possible the identification of the aerodynamic transfer functions that are reported herein. His studies dealt with the hardware and software implementation of a microprocessor based high-speed digital data acquisition and reduction system that was tailored for use in time-varying signal analysis of the unsteady pressure information derived by oscillating the cavity pressure of the CCA in the NPS 2 x 2 foot wind tunnel.

As can be seen from the above document summary, a methodical program has been underway to coordinate the many facets of an experimental effort that was aimed at identifying the many dynamic subtleties involved in unsteady aerodynamics when the cavity pressure and hence the momentum blowing coefficient was harmonically modulated upon the two-dimensional like CCA. Positive results have been obtained at one nominal operating condition showing that unsteady lift and moment behavior can be described by experimentally measured transfer functions. It should be noted that in the context of unsteady aerodynamics, the term "transfer function" implies that many of the niceties of linear system aerodynamics were experimentally evident during the course of the investigations. Also, it was possible to distinguish between the Coanda sheet dynamics, which were viscosity dependent, and the main airfoil pressure coefficient dynamics which were dominated by potential flow considerations.

A final report is in the process of completion describing the primary results in more detail than given in this progress report. However, it was deemed both timely and appropriate to describe some of the principle results in a preliminary form because of possible interactions with parallel hardware design efforts that are underway by other research and engineering groups.

2. DISCUSSION:

2.1 Background:

A brief summary of the Circulation Control Airfoil (CCA) physical definition and steady-flow properties will be presented prior to describing the unsteady aerodynamic results. The CCA, as previously reported in Ref. 1, was a prototype section obtained as a byproduct of the Lockheed Phase I circulation control design feasibility studies. The geometry of the CCA, as tested during this reporting period, was approximately as follows:

Chord:	c = 10.2 inches (0.85 feet)
Thickness ratio:	t/c = 0.214
Airfoil section:	Elliptical with modified trailing edge
Camber:	3.3 percent circular arc
Trailing edge rad.:	r/c = 0.048
Slot location:	x/c = 0.955
Slot gap:	0.016 inches

The refurbished CCA has been evaluated for steady-flow properties in order to establish a zero frequency data basis. Results as reported by Lancaster, Ref. 4, and Kail, Ref. 5, may be highlighted as follows:

a. Lift augmentation ratio, the ratio of lift coefficient production to momentum blowing coefficient ($\partial C_L / \partial C_\mu$) has been observed as having a value of approximately 30 for several moderate angle of attack settings.

b. The center of pressure for lift augmentation has been ascertained as being located at the 54 percent chord point.

c. With tangential jet blowing, the pressure distribution over the rounded trailing edge had a smooth variation and did not exhibit the separation bubbles as evident in measurements reported in Ref. 1 prior to refurbishment of the injection slot.

d. The steel section used to form the upper surface contour of the trailing edge slot had a nominal 0.016 inch gap without gap shims or interference objects in the slot over the entire two foot exposed span of the model. Cavity pressurization bench tests disclosed gap deflection increases typically of 0.001 inch or less under the most severe pressurization conditions expected to be tested.

e. Additional upper surface static pressure orifices at 0.50 and 0.75 chord, away from the midspan instrumented station, confirmed the relatively two-dimensional nature of the flow field in the dominant central span area of the CCA model.

The above remarks are made in a summary fashion in order to establish clearly that the refurbished CCA model behaved in a representative manner, and that the results of subsequent unsteady-flow measurements were interpreted relative to a reasonable data base. The test section dynamic pressure for these investigations was set at approximately 10 psf, which corresponded to a freestream velocity of 92 fps and a model Reynolds

number of 0.5 x 10^6 (based on 0.85 foot airfoil chord length). At this operating condition, momentum blowing coefficients of up to about 0.12 were possible using the available air supply.

Techniques such as used by the DTNSRDC (tangential wall blowing) to compensate for end wall influences upon the airfoil spanwise lift distribution were not employed. Consideration of the steady-flow upper surface static pressure variations in the spanwise direction was made by Kail, Ref. 5. Since the spanwise variation appeared slight until reaching a close proximity to the walls, no compensatory corrections were made to the test technique. A traditional type of wall correction to account for an 0.85 foot chord model operating in the middle of a two foot high wind tunnel could have been considered by the method of images. However, the main purpose of these investigations was to determine if unsteady aerodynamic considerations were of import in the operating frequency range of interest in rotorcraft applications. Therefore, the effort to develop tunnel wall corrections for unsteady as well as steady data seemed premature. This latter comment can be emphasized even more by noting that as of this writing, an analytic prediction of the unsteady aerodynamics associated with an oscillating circulation control superimposed upon an airfoil operating in free-air conditions is not known.

2.2 Unsteady Data Considerations:

Unsteady aerodynamic measurements were made for the situation of an oscillating cavity pressure perturbation superimposed upon a mean or average pressurization level. The nominal or mean value of momentum blowing coefficient was set arbitrarily at approximately $C_\mu = 0.035$, which corresponded to a nominal cavity pressurization level of about 89 psf above ambient static and a mean jet velocity at the slot of approximately 290 fps. It was possible to modulate the oscillating perturbation about the mean with amplitudes up to approximately +/- 50 psf. These relatively large pressure amplitudes were required in order to produce oscillating surface static pressure variations that were distinctly evident above the background tunnel generated pressure noise.

At the model angle of attack of -5.0 degrees, the blowing-off situation corresponded approximately to the zero lift condition. A mean value of momentum blowing coefficient of $C_\mu = 0.035$ resulted in an approximate mean or D.C. value of lift coefficient of $C_L = 1.05$. The mean value of lift coefficient, which was obtained by integration of the recorded values of D.C. surface static pressure, did not change appreciably when cavity pressures were harmonically modulated about the mean value at various amplitudes and frequencies of test interest. This feature of the test results provided additional credence to the linear nature of the model's aerodynamic behavior for the test conditions investigated.

As an aside, the frequency range of interest corresponding to typical rotorcraft applications would typically be considered as being bounded by a reduced frequency value of $k = 0.10$. The upper value of test frequency, 16.0 Hz, corresponded to a reduced frequency value of $k = 0.46$ which is in excess of the normal range of interest. It should be noted

that the high value of reduced frequency did serve a purpose by establishing data trends.

Based upon lessons learned while verifying the data acquisition methods described in Ref. 6, it was decided to record the unsteady analog signal information upon a one-inch tape recorder, with subsequent digital conversion and processing taking place in the shelter and quiet of a laboratory setting away from the wind tunnel. The analog recording at one operating condition of all the surface static pressure information typically required 39 analog records of 30 second duration each. The oscillating pressure in the supply cavity was recorded for each of the analog records and served the role of an analog clock. Other data channels contained signal information from the two Scanivalves and the hot wire in the pressure supply line. For the frequency range of test interest, all pressure systems had approximately the same transfer function between input and transducer. Therefore, the small dynamic corrections were not applied to the readings.

Signal processing results of the unsteady surface pressure data at frequencies of 4.1, 8.0, 11.9 and 16.0 Hz are presented in a normalized fashion inasmuch as it was not possible to conduct each constant frequency data set at exactly the same cavity pressure amplitude value. Therefore, the data were adjusted, based upon linearity assumptions, such that the cavity pressure amplitude corresponded to a value which would produce a lift coefficient of $C_L = 1.0$ if the frequency were zero. As will be noted in the results, this method of data normalization produced consistently reasonable relationships.

Digitizing of the analog signal recordings was made at a sampling rate of 250 samples per second to yield 1000 samples (four seconds) of discretized data for each channel of information at essentially the same sampling instant. The four frequency settings yielded over a half million data points, which were processed by the cross-correlation scheme of Ref. 3 to yield pressure amplitude and phase angle distributions over the airfoil. Appropriate numerical integration over the airfoil chord yielded, as a final result, four aerodynamic transfer function values for circulation control type of lift generation. Details of the data reduction scheme and several sample check out problem situations (which were performed for credibility reasons) will be described in the final report. Credibility concerns were considered of paramount importance since there was no previous unsteady aerodynamic information available on CCA type aerodynamics to confirm or deny the gain and phase shift determinations for the Coanda sheet, airfoil lift and damping moments.

2.3 Coanda Sheet Results:

Hot-wire studies by Kail, Ref. 5, confirmed that the Coanda sheet formed by tangential jet blowing was composed of turbulent natured flow. Unsteady pressure data results in a normalized form are shown for the viscous dominated Coanda sheet region, Fig. 1. Both pressure coefficient amplitude and phase shift (relative to the cavity pressure perturbation) are shown as a function of dimensionless surface length. Since the trailing edge region closely approximated a circular arc, an alternate scale showing angular coordinate relative to the slot injection region is also shown.

Although at first glance, Fig. 1 may appear "busy", facts to be noted would include:

a. The normalized pressure amplitude variation in the Coanda sheet region exhibits the same traits as previously observed in steady flow; namely, a smooth buildup in pressure coefficient to a peak followed by a decrease to a region near the chord plane where the sheet separated from the airfoil. Obviously, the average location of the rear stagnation point was dependent upon the mean value of momentum blowing coefficient.

b. The pressure amplitude did not show any significant dependence upon frequency, as evident by the cross-hatched fairing.

c. At zero frequency, one would expect the phase angle of Coanda sheet pressures to lead (or lag) the cavity pressure by 180 degrees since a positive pressure perturbation in the cavity would increase the Coanda sheet tangential velocities, and hence lower the corresponding surface static pressures. Note that the 180 degree lead angle is lessened by frequency increase, but the phase angle shift is essentially uniform in the attached Coanda sheet region.

d. Near the flow detachment point, the phase angle rapidly changes to a value of approximately zero degrees since the pressure perturbations on the lower surface of the airfoil ahead of the Coanda sheet detachment point tend initially to be in phase with the cavity pressures. This aspect will be brought out again during discussion of Fig. 3. It is interesting to note that it was only in this region that the pressure wave had a significant second harmonic present, presumably due to the fact that a local static pressure orifice was exposed to the flow domain on either side of the (oscillating) Coanda sheet's rear stagnation point.

e. The phase angle variations along the airfoil surface ahead of the injection slot exhibited similar traits to the Coanda sheet phasings when frequency was varied. However, the exact surface variation in the neighborhood of the slot was not well defined, hence dashed curves were used where appropriate to denote a degree of curve fairing uncertainty.

The relatively constant variation of pressure signal phase shift in the Coanda sheet, combined with a trend that the pressure amplitude did not appear frequency dependent, suggested that the phase shift with frequency variation might be due to other physical factors. Therefore, the pressure signal phase shift variation with reduced frequency was cross plotted, Fig. 2, for a Coanda sheet station about 2.5 percent of chord distance downstream from the jet injection slot. The significant feature to note is that the phase shift appears to behave linearly with respect to frequency.

Classical control theory would suggest that the Coanda sheet behavior was dominated by a Transportation Lag type of phenomena since the transfer function for Transportation Lag is of the form $\exp(-Ts)$.
For an $\exp(-Ts)$ situation:

Gain: $|G(f)| = 1$

Phase: $\phi(f) = -2\pi f\, T$

The slope of the phase shift curve, Fig. 2, allows the transport time lag, T, to be estimated as approximately T = 0.0043 seconds. It is possible to relate the time lag to an equivalent transport lag distance that might correspond to some measure of the physical laws governing the flow from a reservoir or supply source into a smoothly contracting two-dimensional slot. Confirmation of the scaling laws should be derivable by continuing the test program at other operating conditions and focusing the measurements to identify this phenomena. Finally, it should be recognized that at the present time, the only capability for relating the jet flow velocity at the slot exit to reservoir conditions is dependent upon gas dynamic relationships for steady flow with possible empirical modifications for orifice coefficients.

2.4 Main Airfoil Results:

For sake of clarity, the relations used to determine the unsteady lift coefficient expressions will be stated. In general, an oscillating lift coefficient would be expressed relative to a physically significant time base. For the results reported herein, the time base was the harmonically varying cavity pressure perturbation signal. Typical expressions for the lift coefficient would take the form of either

$$C_L \sin(\omega t + \phi_L) \quad \text{or} \quad C_L \cos(\omega t + \phi_L) .$$

Furthermore, it should be realized that a frequency dependence exists in a functional sense such that:

$C_L = C_L(\omega)$ = Amplitude of lift coefficient

$\phi_L = \phi_L(\omega)$ = Phase angle relative to a time base

The unsteady lift coefficient may be expressed more precisely by:

$$C_L \sin(\omega t + \phi_L) = \left[C_L \cos\phi_L\right]\sin\omega t + \left[C_L \sin\phi_L\right]\cos\omega t$$

or ...(1)

$$C_L \cos(\omega t + \phi_L) = \left[C_L \cos\phi_L\right]\cos\omega t - \left[C_L \sin\phi_L\right]\sin\omega t$$

where

$C_L \cos\phi_L$ = In-phase lift contribution

$C_L \sin\phi_L$ = Out-of-phase lift contribution

The in-phase and out-of-phase lift coefficients were obtained from the pressure distribution information by first integrating the pressure distributions to establish the in-phase and out-of-phase normal and chord force coefficients followed by a suitable coordinate transformation from body to wind axes. Equation 2 below shows the expression that defines $C_N \cos\phi_N$. Similar expressions were employed to obtain $C_N \sin\phi_N$, $C_C \cos\phi_C$ and $C_C \sin\phi_C$.

$$C_N \cos{}_N = \int_0^1 \left[(C_p \cos{})_{lwr} - (C_p \cos{})_{uppr}\right] d(x/c) \qquad \text{...(2)}$$

The coordinate rotational transformation was of the form:

$$C_L \cos\phi_L = (C_N \cos\phi_N)\cos\alpha - (C_C \cos\phi_C)\sin\alpha \qquad \text{...(3)}$$

where

α = Geometric angle of attack of the CCA chord plane relative to the freestream velocity vector.

Figure 3 illustrates the phase angle variation over the airfoil chord for both the upper and lower surfaces as the cavity pressure perturbation was oscillated at 16.0 Hz. For comparative purposes, one would expect the effect of the Coanda sheet upon surface static pressures at zero frequency to produce 180 and 0 degree phase angles for the upper and lower surfaces respectively. From Fig. 3, one may observe sizable phase shifts taking place for the situation of the Coanda sheet harmonically oscillating at 16.0 Hz, with up to an 80 degree (1.4 rad.) lag change (relative to zero frequency) occurring on the forward portion of the airfoil. The phase angle variation defined a smooth curve over the airfoil chord with the exception of the phase angle "jump" across the front and rear stagnation points.

In the neighborhood of (x/c) = 1.0, the cluster of upper surface pressures exhibited a phase shift of approximately 155 degrees, with the 25 degree difference from 180 degrees reflecting the influence of transport lag phenomena upon the Coanda sheet pressures. Similarly, the cluster of lower surface pressure phase angles near to a zero degree value is an indication of the phase angle situation just forward of the Coanda sheet departure point which represents the airfoil rear stagnation point.

Figures 4 and 5 show unsteady pressure distributions over the airfoil in the form of $C_p \cos\phi$ and $C_p \sin\phi$ vs. (x/c) respectively. The pressure amplitudes, as stated previously, reflect normalization corrections using the cavity pressure perturbation amplitude such that the lift coefficient would be unity at zero frequency.

The presence of the tangential jet blowing and the Coanda sheet is evident in the trailing edge regions by local curve "peaking". However, the leading edge pressure "peaking" from circulation control is not evident in Fig. 4, partially due to the influence of the cosine term.

Integration of the areas described by the curves of Figs. 4 and 5 yielded estimates as follows:

$$C_N \cos\phi_N = 0.569 \quad \text{and} \quad C_N \sin\phi_N = -0.444$$

Similar integrations for chord force coefficients yielded estimates of:

$$C_C \cos\phi_C = 0.129 \quad \text{and} \quad C_C \sin\phi_C = -0.057$$

Application of eqn. 3 for an angle of attack of -5.0 degrees provided the result, in a normalized form, that the in-phase and out-of-phase lift coefficients were:

$$C_L \cos\phi_L = 0.578 \quad \text{and} \quad C_L \sin\phi_L = -0.447 \qquad \text{...(4)}$$

Continuing the example further, one may obtain the magnitude and phase of the lift coefficient quite readily using the information of eqn. 4. Note that since the results were normalized to a unit value of lift coefficient at zero frequency, the C_L amplitude may then be viewed as a gain term in the aerodynamic transfer function for lift.

$$C_L = \left[(C_L \cos\phi_L)^2 + (C_L \sin\phi_L)^2\right]^{1/2} = 0.731$$

and $\qquad\qquad\qquad\qquad\qquad\qquad$ ...(5)

$$\phi_L = \tan^{-1}\left[(C_L \sin\phi_L)/(C_L \cos\phi_L)\right] = -37.7 \text{ degrees}$$

The result of eqn. 5 may be found plotted on Fig. 6 with the symbol ($\triangle$) as a function of the reduced frequency value corresponding to 16.0 Hz. Figure 6 represents the <u>first</u> experimental results of the aerodynamic lift transfer function due to unsteady circulation control about a mean (or average) momentum blowing coefficient of $C_\mu = 0.035$. The lift transfer function, which is in general a complex natured quantity, is defined by:

$$G(k) = \frac{|C_L(k)|}{C_L(k=0)} \exp(i\phi_L) \qquad \text{...(6)}$$

where

k = Reduced frequency = $\omega c/2U$

i = Imaginary quantity = $(-1)^{1/2}$

ω = Circular frequency = $2\pi f$, sec^{-1}

General features apparent from the aerodynamic lift transfer function curve, Fig. 6, are that increasing the frequency produced a gradual attenuation in gain and a smooth growth in phase lag. It is a temptation to compare these results with a classical control system that has a simple pole since the transfer function curve exhibits many of the attributes of a simple pole system. However, it should be borne in mind that these transfer function curves include, in a serial manner, the consequences of the Coanda sheet transfer function. Hence, until a clearer picture of the scaling laws for the Coanda sheet region of the airfoil becomes available, it might be premature to generalize too broadly.

It has been stated earlier that the center of pressure of steady lift on the CCA due to circulation control has been determined as being at approximately the 54 percent chord point when the airfoil was operated in a linear region. A similar type of description was sought for the unsteady pitching moment coefficient. It was found during a search for an unsteady circulation-control center of pressure location that the in-phase and out-of-phase pitching moment coefficients did not concurrently vanish at any chordwise location. This fact suggested the presence of damping type terms in the unsteady pitching moment coefficient.

The unsteady pitching moment transfer function was investigated at several chord locations in the mid-chord neighborhood. From this study, the unsteady pitching moment transfer function at the $(x/c) = 0.54$ location, corresponding to the steady flow center of pressure location, showed physical significance. Figure 7 presents the corresponding pitching moment transfer function curves, from which the deduction may be made that a damping type moment exists based upon the following observations:

a. The magnitude of pitching moment coefficient vanishes as frequency goes to zero.

b. The phase angle tends to -90 degrees as frequency goes to zero.

The exact nature of the damping moment is not clear at this time. The amplitude varies with frequency in a nonlinear manner which suggests that an analytic expression for this term might include some terms including the reduced frequency, k, in much the same manner as in conventional airfoil unsteady aerodynamics. Also further thought, probably using simple engineering examples, might be helpful in establishing whether the phase angle is such as to provide a stable damping moment.

3. CONCLUDING REMARKS:

An experimental technique has been established which allows the measurement of unsteady airfoil surface static pressures and subsequent digital data processing for the express purpose of defining aerodynamic transfer functions of Circulation Control Airfoils.

Recent results for the CCA model at one angle of attack, one tunnel airspeed, and harmonic oscillation of the cavity pressure at four frequency values using one average value of momentum blowing coefficient have been reported. A summary of the results, some of which are original to this document, includes:

a. The airfoil behaved in a linear manner.

b. The mean or average value of lift coefficient was not altered during unsteady blowing.

c. The frequency response traits of the Coanda sheet region suggest the presence of transportation lag between the pressure cavity and the blowing slot.

d. The overall airfoil lift transfer function from harmonic circulation control variations had a behavior quite similar to that of a simple pole in classical control theory.

e. A frequency dependent pitching moment about the 54 percent chord center of pressure location for circulation control type lift was evident with the attributes of aerodynamic damping being shown.

A final report is under preparation that describes in more detail the results presented herein for the model at an angle of attack of -5.0 degrees. Similar measurements at an angle setting of zero degrees also will be presented, which should provide added confirmation to the conclusions. One set of data with rotating shutters (harmonic tunnel blockage) synchronized with the cavity pressure oscillations were recorded, and the present analysis tools should make possible an illuminating evaluation of the combined dynamics of the tunnel and airfoil. Finally, a set of hot-wire measurements of the oscillating velocity profile in the supply line for a fully developed turbulent flow environment will provide an interesting observation relative to velocity profile similarity assumptions.

The existence of carefully developed experimental tools plus a quality model setup suggests an economical program continuation which could include:

a. Verify scaling laws for the Coanda jet flow region by conducting experiments at other select test conditions of momentum blowing coefficients and pressure perturbation amplitudes.

b. Verify complete airfoil dynamic behavior by operating at select alternate conditions of:
   - o tunnel dynamic pressure
   - o momentum blowing coefficient
   - o pressure perturbation amplitudes
   - o alternate angle of attack settings including near to stall
   - o model surface alterations such as grit, and
   - o slot gap alterations.

In parallel, an analytical solution should be sought for predicting the unsteady aerodynamics of the airfoil due to an oscillating rear stagnation point. This effort would in essence correspond to separating the overall system transfer function and allow a focus on a portion of the problem amenable to potential flow analysis. This analytic work, combined with an experimental "harvesting" of the information awaiting to be identified should provide a valuable contribution towards increasing the understanding of the unsteady flow field about a Circulation Controlled Airfoil. Finally, it should be recognized that the goal of these research endeavors has been oriented towards supporting the serious usage of the CCA in rotorcraft applications by providing aerodynamic information that will improve upon previous quasi-steady assumptions employed in system design and analysis.

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It is through the efforts of the above staff, numerous students and many other individuals in the Department of Aeronautics, NPS that the favorable results must be credited. The undersigned had the good fortune at the completion of the reporting period of describing the end product of many individual contributions and any inadvertent errors of omission must rest as a human limitation of the undersigned.

L.V.S.

4. REFERENCES:

1. Miller, J.A. and Schmidt, L.V., "Progress Report No. 3, Circulation Control Airfoil Study", NPS, 12 December 1976.

2. Bauman, J.L., LT, "Development of a Control Valve to Induce an Oscillating Blowing Coefficient in a Circulation Control Rotor", M.S. Thesis, NPS, December 1976.

3. Pickelsimer, B.M., LT, "Data Reduction for the Unsteady Aerodynamics on a Circulation Control Airfoil", M.S. Thesis, NPS, March 1977.

4. Lancaster, E.J., LT, "Initial Unsteady Aerodynamic Measurements of a Circulation Controlled Airfoil and an Oscillating Flow Wind Tunnel", M.S. Thesis, NPS, June 1977.

5. Kail, K.A., LT, "Unsteady Surface Pressure and Near-Wake Hotwire Measurements of a Circulation Control Airfoil", Eng. Thesis, NPS, to be published.

6. Englehardt, C.D., LT, "Data Acquisition System for Unsteady Aerodynamic Investigation", M.S. Thesis, NPS, June 1977.

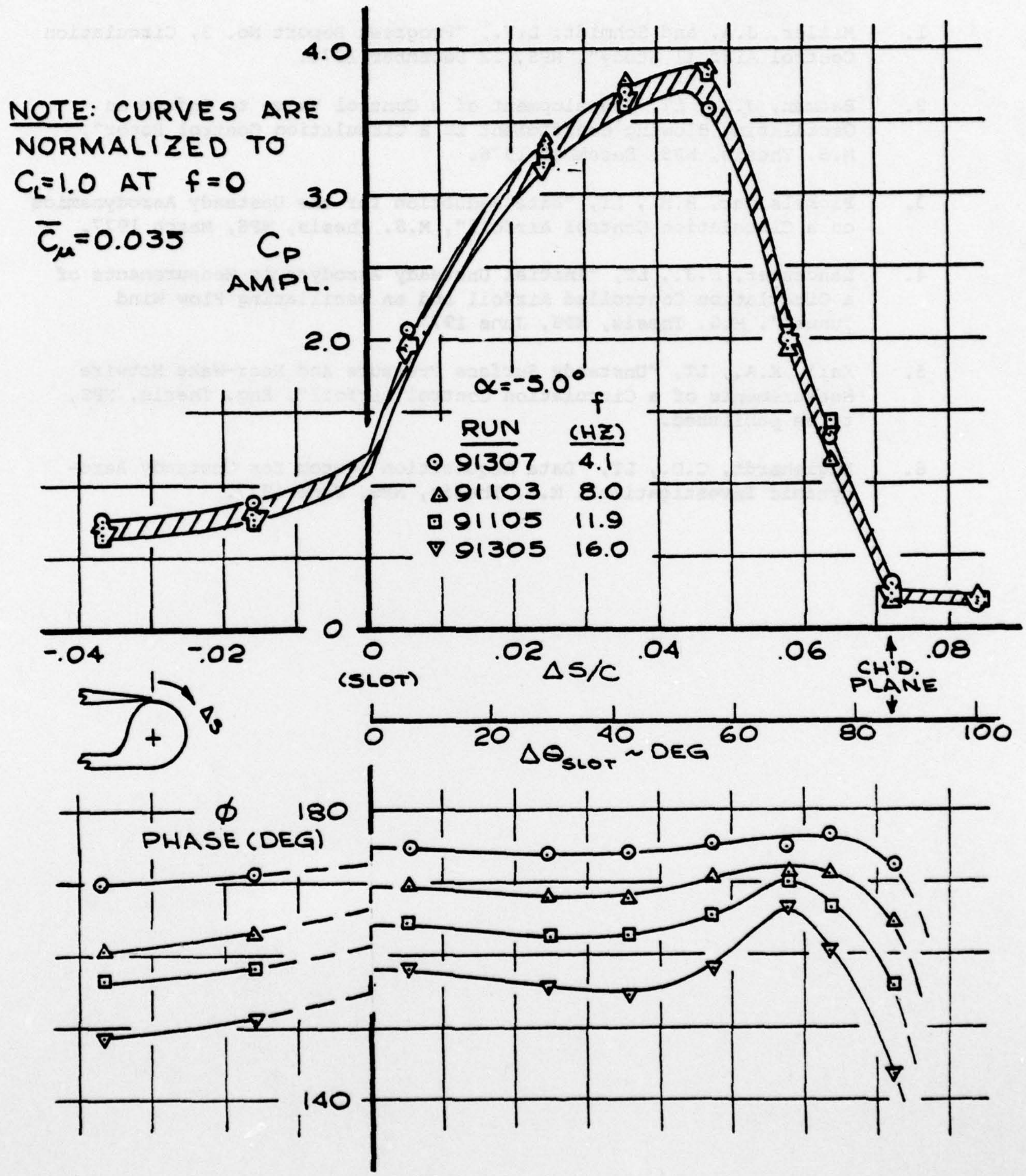


FIG. 1: COANDA SHEET PRESSURE DYNAMICS

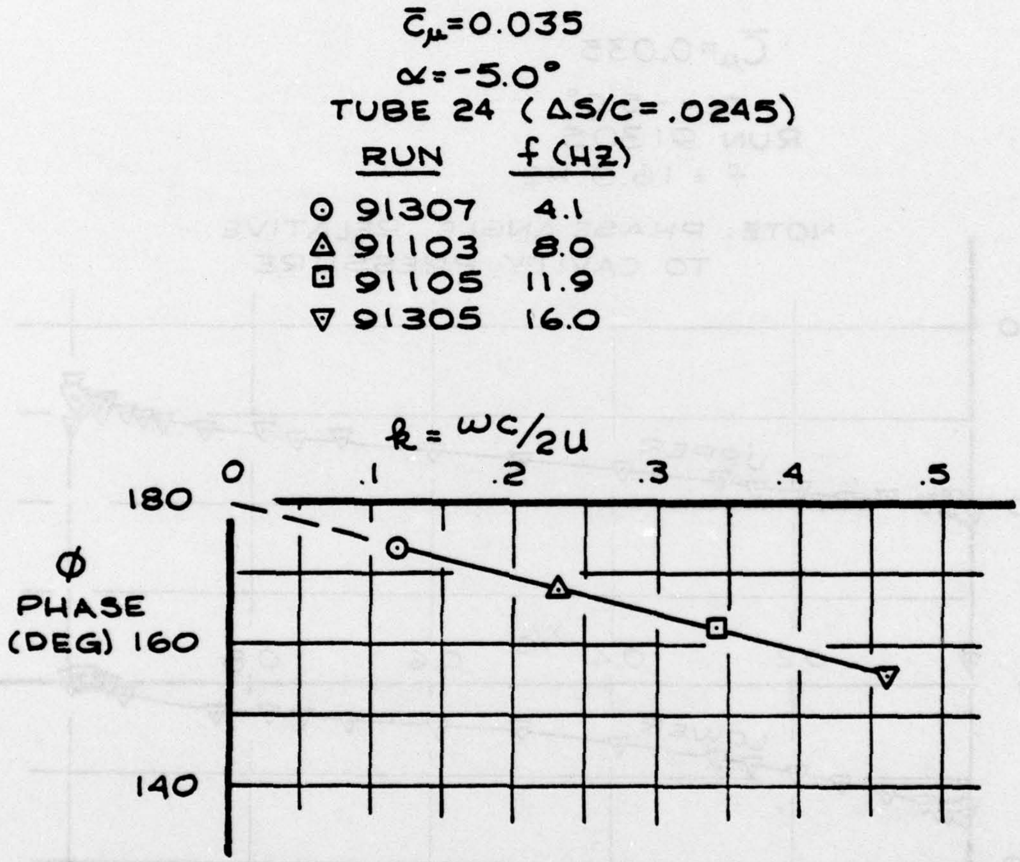


FIG. 2: COANDA SHEET PHASE LAG

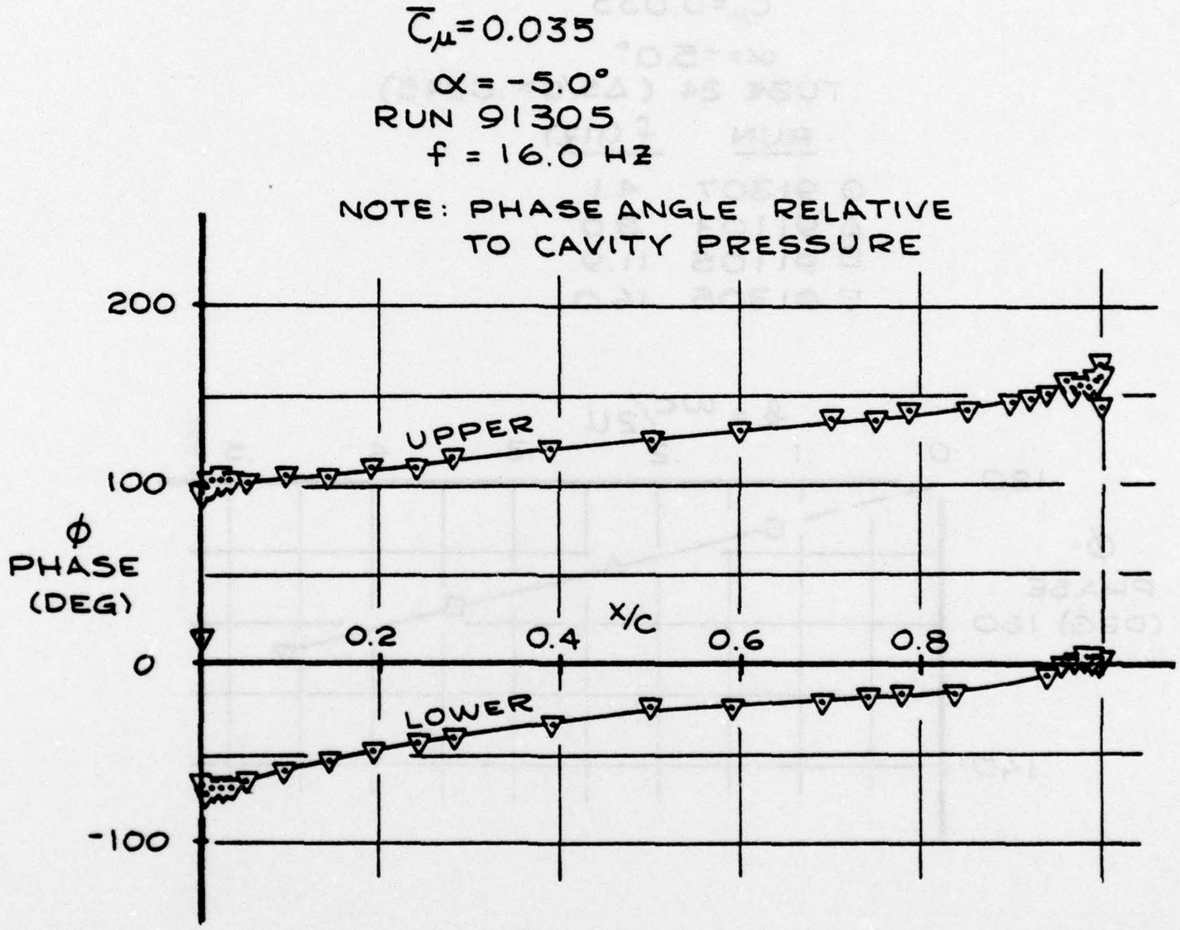
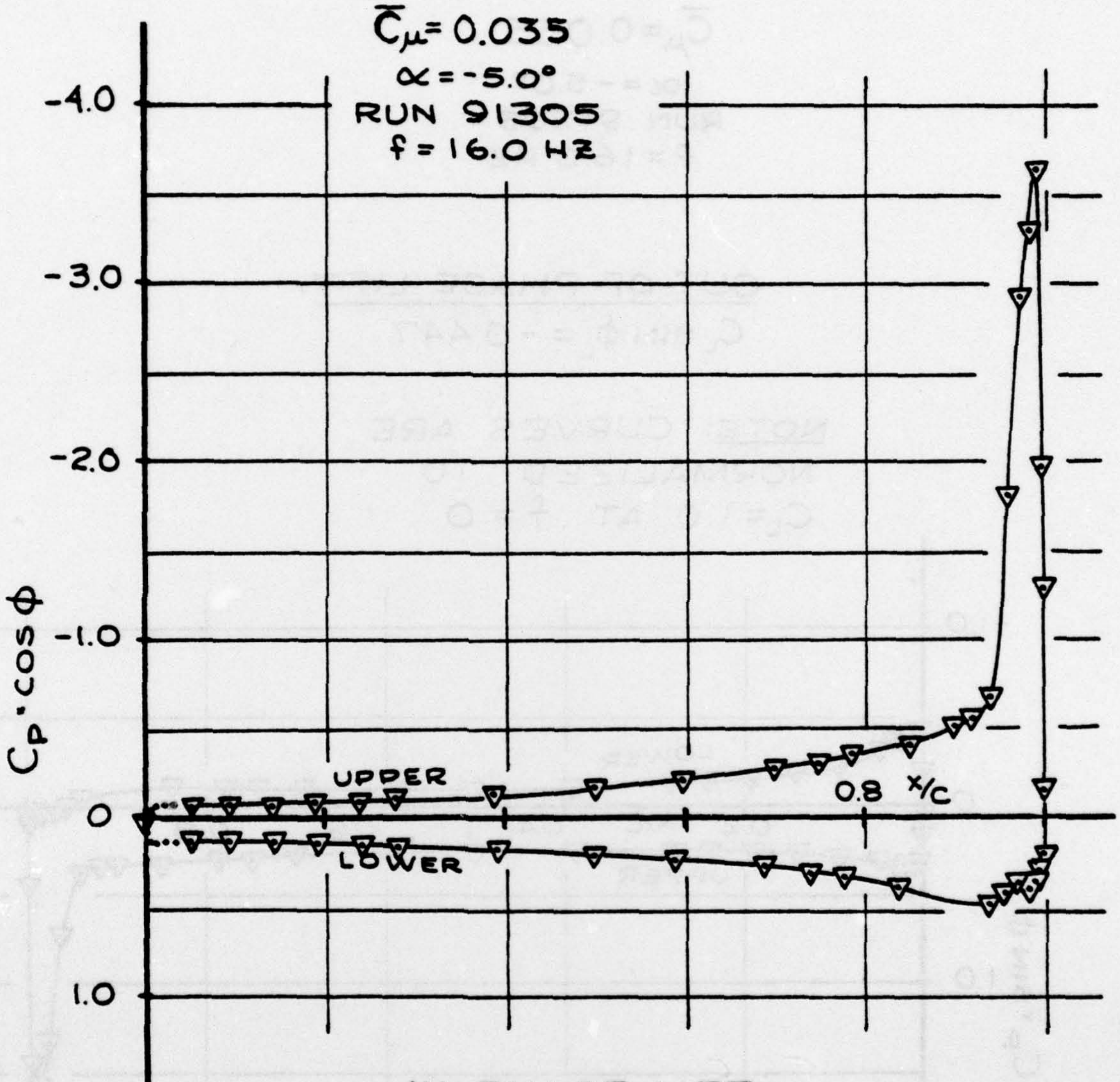


FIG. 3: AIRFOIL SURFACE PRESSURE PHASE ANGLES



IN-PHASE LIFT:

$C_L \cos\phi_L = 0.578$

NOTE: CURVES ARE NORMALIZED TO $C_L = 1.0$ AT $f = 0$

FIG. 4: AIRFOIL IN-PHASE PRESSURE DISTRIBUTION

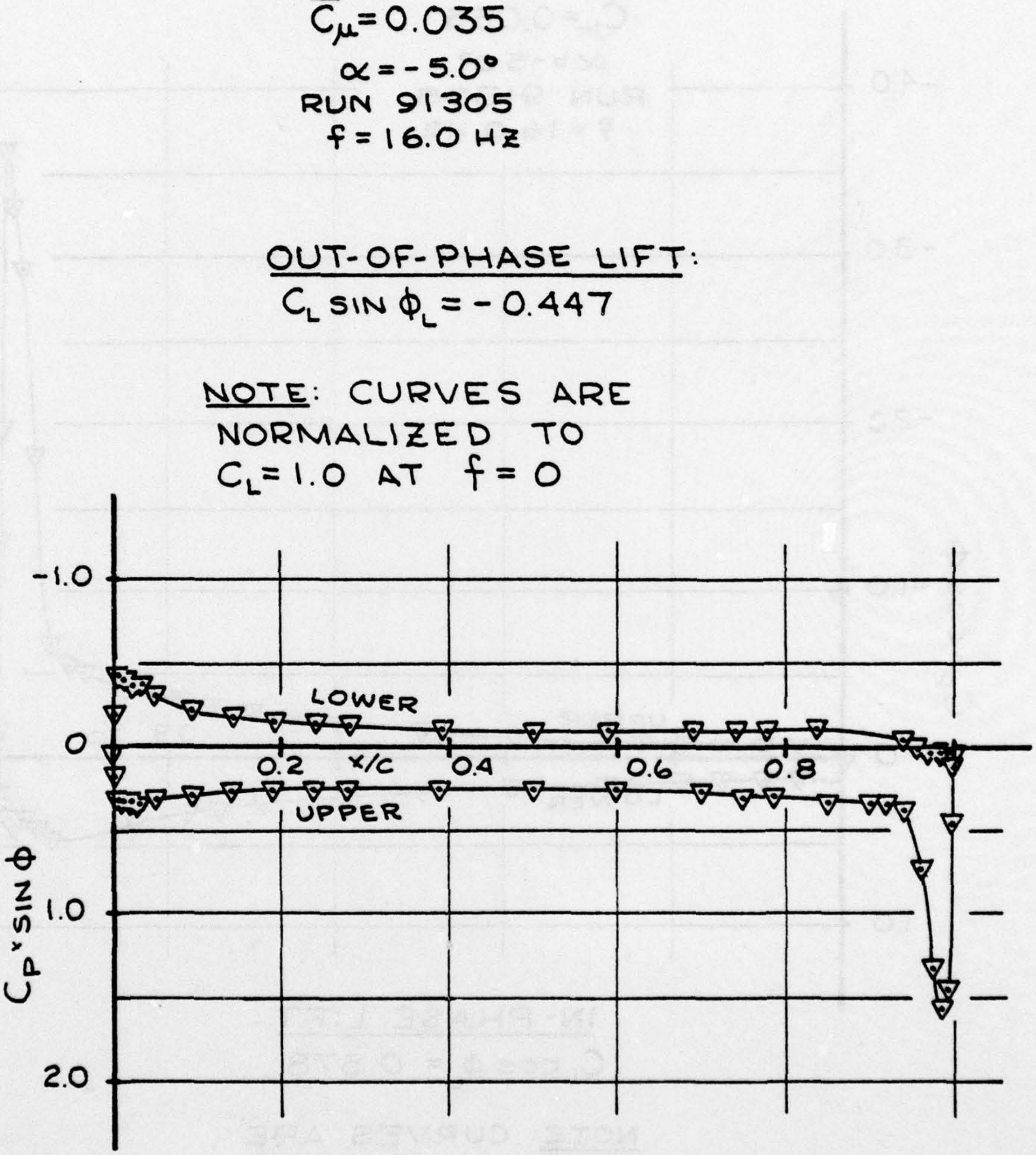


FIG.5: AIRFOIL OUT OF PHASE PRESSURE DISTRIBUTION

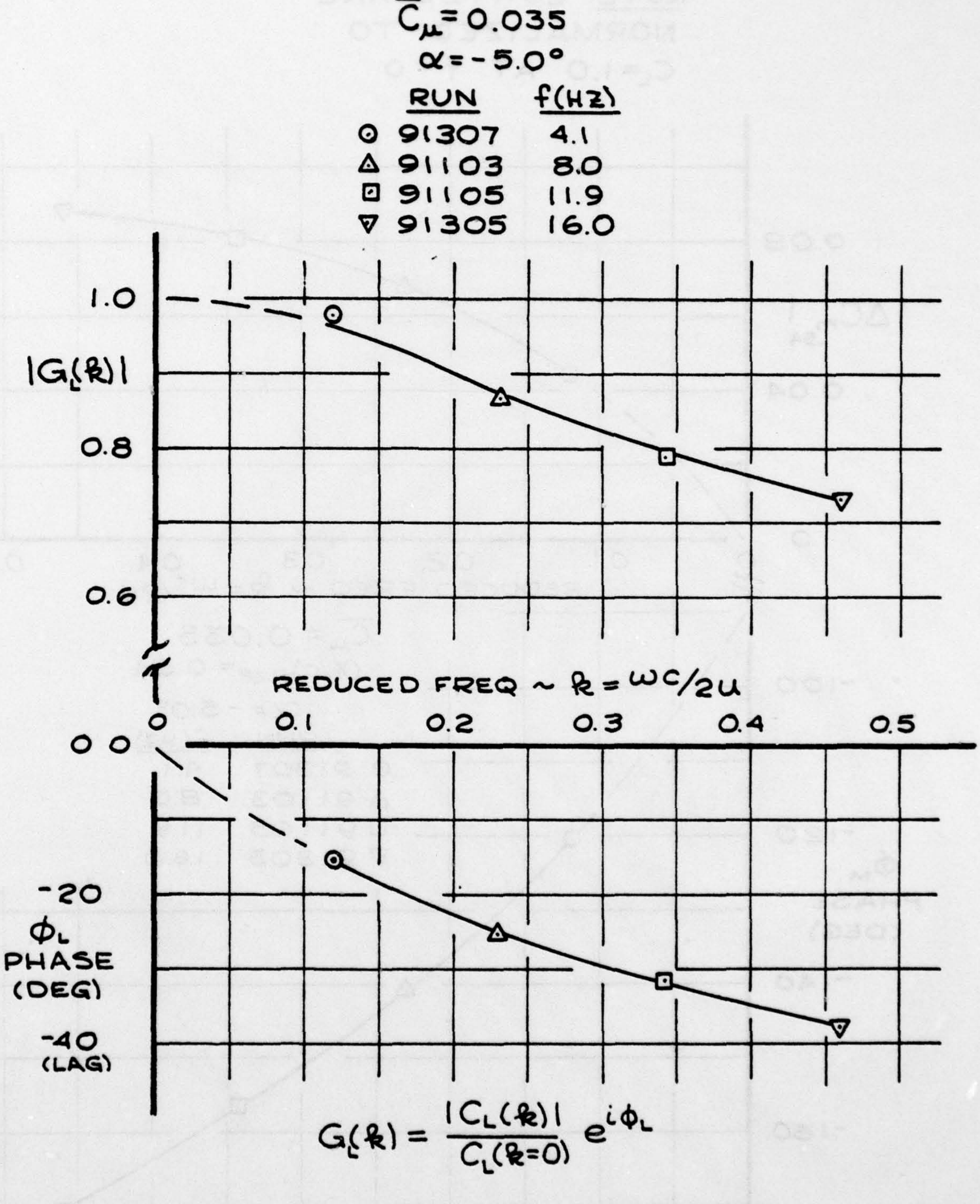


FIG. 6: CIRCULATION CONTROL LIFT TRANSFER FUNCTION

NOTE: CURVES ARE NORMALIZED TO $C_L = 1.0$ AT $f = 0$

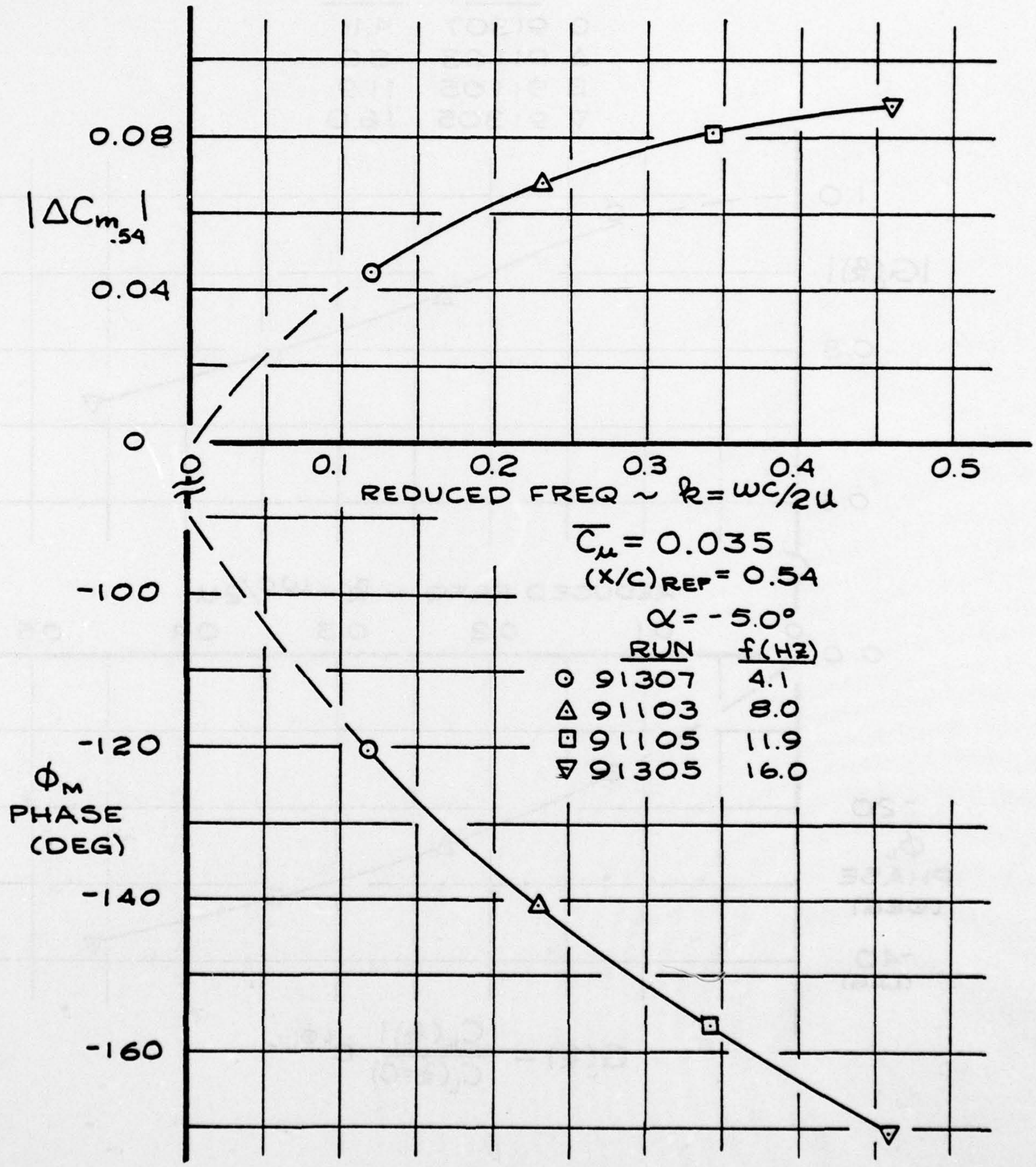


FIG. 7: PITCHING MOMENT DYNAMICS

APPENDIX A:

Abstracts of References 2 to 6.

Reference 2:

Bauman, J.L., LT, "Development of a Control Valve to Induce an Oscillating Blowing Coefficient in a Circulation Control Rotor", M.S. Thesis, NPS, December 1976.

Abstract: The Circulation Control Rotor concept makes it possible to achieve large changes in lift coefficient, without changing angle of attack, by making only small changes in blowing coefficient. The concept has great potential in the area of rotary-wing aerodynamics, where implementation will require the generation of oscillating blowing coefficients. In order to examine the response of a circulation control airfoil to such an oscillating blowing coefficient, a simple control valve system was designed and built. The effectiveness of the control valve in oscillating the blowing coefficient at various frequencies and amplitudes was examined. An attempt to determine the effect of this oscillation on the instantaneous lift coefficient of the rotor was not successful.

Reference 3:

Pickelsimer, B.J., LT, "Data Reduction for the Unsteady Aerodynamics on a Circulation Control Airfoil", M.S. Thesis, NPS, March 1977.

Abstract: Calculating the lift, drag and pitching moment coefficients for an airfoil from the static pressure distribution obtained from wind-tunnel tests is a routine task when steady flow is considered, but it is much more complicated when the airfoil is operating in an unsteady flow field, similar to that experienced by a helicopter rotor blade, produced by an oscillating wind tunnel. A data reduction routine capable of condensing the large numbers of data associated with the unsteady investigation, as well as a numerical integration algorithm for the unsteady aerodynamic coefficients, were developed; however, no unsteady data were collected due to hardware failures. The ability of the program was demonstrated on previously obtained steady and quasi-steady data and sample results were presented.

Reference 4:

Lancaster, E.J., LT, "Initial Unsteady Aerodynamic Measurements of a Circulation Controlled Airfoil and an Oscillating Flow Wind Tunnel", M.S. Thesis, NPS, June 1977.

Abstract: Steady state results of lift developed by varying the momentum blowing coefficient (C_μ) upon a refurbished Circulation Control Rotor (CCR) airfoil section were favorable. This thesis was an experimental investigation to evaluate quantitatively whether the steady state results could be applied by a quasi-steady assumption when a harmonic perturbation of C_μ was superimposed upon the steady value. Results suggested an attenuation in the dynamic transfer function of dC_P/dC_μ as the oscillating blowing frequency was increased.

The oscillating flow wind tunnel in which the CCR airfoil section was tested exhibited a relationship between pressure and velocity amplitude not in accordance with quasi-steady small perturbation theory. Initial measurements indicated that the RMS C_P perturbation was an order of magnitude greater than the normalized RMS velocity perturbation. To clarify this situation further, investigations were conducted to establish a dynamic frequency response calibration of the wind tunnel. Results confirmed the order of magnitude difference between the RMS C_P and normalized RMS velocity perturbations, indicating that the tunnel flow environment was governed by Euler's equation in its complete form rather than with simplifications which lead to the quasi-steady small perturbation theory.

Reference 5:

Kail, K.A., LT, "Unsteady Surface Pressure and Near-Wake Hotwire Measurements of a Circulation Control Airfoil", Eng. Thesis, NPS, to be published.

Abstract: The large lift coefficient changes attainable with Circulation Control Airfoils through small changes in boundary layer blowing suggest rotary wing cyclic control can be obtained through modulation of the blowing. Static pressure distributions were obtained to assess the unsteady behavior of a Circulation Control Rotor in a two-dimensional flow. A constant-radius hotwire wake traversing mechanism was constructed to augment the pressure data and to study the flow phenomena occurring in the region of Coanda jet separation. Through correlation of turbulence intensity data with pressure data, it was discovered that the point of Coanda jet separation could be located using the hotwire. The objective of these tests was accordingly expanded to include correlation of the location of separation with flow parameter variation.

Reference 5: (cont'd.)

Although steady flow, steady blowing test results were favorable, the unsteady blowing test was restricted in scope because of an inability of the injection air compressor to provide an adequate flow, and because the real-time data acquisition system was not completed in time for these tests. From mean value and RMS data obtained during oscillatory blowing, no increase in average lift augmentation above that produced in equivalent steady blowing was discernible.

Reference 6:

Englehardt, C.D., LT, "Data Acquisition System for Unsteady Aerodynamic Investigation", M.S. Thesis, NPS, June 1977.

Abstract: This paper describes the design and implementation of a microprocessor based high-speed digital data acquisition and reduction system suitable for use in time-varying signal analysis as encountered in unsteady aerodynamic investigation. A microprocessor, flexible disk drive and an analog-to-digital conversion module were the main components which were integrated to form a 32 channel, 12 bit resolution data acquisiton system capable of 1000 Hz sampling rate and permanently storing over 250,000 bytes of data on magnetic diskette. Subsequent to the data logging process, the same system was capable of serving as a general purpose computer utilizing the popular BASIC scientific programming language.

The system was qualified for accuracy and functional performance through a series of controlled exercises, and was then applied to an actual investigative task to determine further its utility and value.

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